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Performance and runoff coefficient of permeable concretes subjected to heavy rainfall simulations

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ABSTRACT

The use of permeable concrete pavements can mitigate flooding in densely populated areas by serving as a functional and sustainable mechanism for surface water absorption and drainage. However, it is found that the performance of the pavement is often limited to low and moderate flows and that the absorption capacity of the concrete matrix decreases as the flow rate increases. Therefore, the present study was developed aiming to evaluate the potential to reduce runoff in permeable concrete pavements subjected to simulations of successive events of heavy rainfall. For this purpose, 2 binary combinations of coarse aggregates were used, varying the cement consumption and the water/cement (w/c) ratio. The samples were submitted to simulations of heavy and sequential rainfall, with evaluation of the volume of water absorbed and the runoff. The mechanical and hydraulical properties of the permeable pavements were evaluated, as well as the characteristics of the area and volume of the internal and superficial pores. Among the results, specific weight stands out as the parameter that showed the highest linear correlation with the mechanical and hydraulic behavior of the specimens. It was also found that the runoff coefficient had a moderate negative linear correlation with the average pore size of the surface of the pavement. Finally, the permeable concrete pavements investigated were found to have the potential to reduce surface runoff in densely populated areas that are prone to frequent flooding, thus playing a critical role in mitigating the problems associated with stormwater runoff.

Keywords: Permeable concrete; Heavy rainfall simulations; Permeability coefficient; Porosity; Runoff coefficient.

1. INTRODUCTION

The accelerated urban advance as consequence of the rural exodus and population growth, added to the cities once unimaginable land occupation and use arrangements. Intensive sealing of natural and vegetated land has been observed, especially in developing countries, leading to greater need for environmentally friendly sanitation infrastructure such as water supply systems, sanitary sewerage, and storm water drainage.

Surface water drainage and water resources management have an impressive impact on the quality of life of people and communities, especially in regions where inefficient drainage systems combined with adverse climatic and environmental conditions result in frequent flooding, yielding to human and material losses. Therefore, several authors emphasize the importance of public policies for education, prevention, control, and management of surface water, as well as a diagnosis of the infrastructure used and alternative proposals for the mitigation of urban flooding. [1–3].

In this context, several guidelines were developed for the creation of functional and sustainable building systems, technologies, and materials [4, 5]. In 2012, the Chinese government launched an integrated action plan between traditional and innovative drainage technologies, with the aim of developing so-called sponge cities, flexible to climate change, urban environment altering and population growth. The sponge cities plan is conceptually linked to resilient, adaptable, and sustainable cities equipped with drainage systems capable of absorbing, storing, purifying and reusing rainwater [6–9].

In this sense, the use of permeable concrete pavements stands out. Permeable concrete is a special paving material developed by reducing or removing fines from the composition of a conventional concrete so that the matrix consists only of cement paste and coarse aggregates, ensuring the presence of interconnected pores with high capacity for infiltration of fluids [10–12]. Permeable concrete drainage technology was originally used in Europe in the 19th century, but it was not until after the end of World War II, when several war-ravaged countries

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lacked funding and raw materials, that it was used as a drainage system for houses and as a management component for urban drainage [13].

The properties of the pores in the concrete matrix not only allow infiltration of liquids and reduce surface runoff, but also have a strong influence on the strength of the material. Among the parameters that can affect the properties of the pores are the aggregates used and the cement paste. Studies have found that a cement paste volume to interparticle pore ratio of 50% provides the best balance between strength and permeability [14]. On the other hand, some authors have found that it is possible to obtain higher mechanical strength by optimizing the particle size of coarse aggregates and reducing the diameter of aggregates without affecting the pore properties [11, 15].

By interconnecting pores, permeable concrete can absorb rainwater and prevent surface runoff [10, 12]. In this sense, several studies have analyzed the potential of permeable concrete pavements to reduce runoff coefficient (Table 1). Permeable concrete pavements showed great variability in their ability to reduce the volume of surface runoff.

However, as shown in Table 1, most of the relevant literature does not address the performance of permeable pavements exposed to rainfall amounts greater than 100 mm. It is also well established that the performance of pavements varies widely under different rainfall regimes: the efficiency of permeable pavement in reducing the amount of water runoff varies from 31 up to 100% for rainfall up to 100 mm. Such results are observed because the ability to absorb and retain stormwater in permeable concrete depends on the characteristics of the pavement surface, the intensity, volume, and frequency of the rainfall, and the presence of solid residues carried by the water that fill the surface pores and limit absorption in the concrete matrix [24, 25]. Therefore, some authors suggest that the pavement should be recommended for regions with low to moderate intensity rainfall because it is not economically attractive to develop pavements with these properties for regions with high intensity rainfall. [17, 26].

The municipality of Belém, Amazon rainforest, Brazil, where this study was conducted, is characterized by the influence of the intertropical convergence zone and instability lines, wind circulations, and convective clusters as determinants of the local precipitation regime [27].The annual precipitation index is characterized by months with more than 400 mm of rain, especially in the first half of the year (February, March and April), and less rainy months, when the rainfall reaches 130 mm/month, such as August, September, October and November, according to official data from the Brazilian National Institute of Meteorology (INMET) for the last 100 years. The high flow rate, related to factors such as the sealing of the topsoil layers, heavy rainfall (up to 3000 mm/year), strong changes in the natural trajectories of sub-basins due to the urbanization process and the incompatibility of drainage systems with the regional reality, has led to several flooding sites in the city [28, 29].

Moreover, the limitations of using permeable pavements arise from the low mechanical strength of the material due to the high porous content of the concrete matrix and its proximity, which favors the development of cracks and fractures [11]. Several recent studies address the use of supplementary cementitious materials as alternatives to optimize the mechanical performance of concrete by using components with high synergy and reactivity to reduce the pore diameter of the concrete matrix [30–33] or the use of nanoparticles in cementitious composites to provide higher strength and durability to the mixes [34]. In turn, in the present study, it was decided to optimize the packing of the coarse aggregates for the compaction of the permeable concrete matrix [34].

Table 1: Reduction of surface runoff volume from the use of permeable concrete pavements.

STUDY	RAINFALL VOLUME	REDUCTION OF SURFACE RUNOFF VOLUME (%)
RUSHTON *et al*. (2001) [16]	72 mm	35%
DREELIN *et al*. (2006) [17]	18,5 mm	93%
KWIATKOWSKI *et al*. (2007) [18]	–	100% infiltration for rainfall less than 50 mm
BEAN *et al*. (2007) [19]	97 mm	31%
COLLINS *et al*. (2008) [20]	183 mm	37%–66%
DRAKE *et al*. (2012) [21]	51,6 mm	57%
WINSTON *et al*. (2018) [22]	2,5 mm–89,2 mm	98%
ALAM *et al*. (2019) [23]	70 mm	98%
LIU *et al*. (2020) [24]	84,8 mm–85,13 mm	42,5%–52,5%

The limited mechanical resistance and absorption capacity for heavy rainfall seems to limit the widespread use of permeable concrete pavements for stormwater drainage in regions with virtually year-round rainfall. Therefore, the present study was developed with the aim of evaluating the potential for reducing runoff in permeable concrete layers subjected to simulations of successive events of heavy rainfall, characteristic of regions with a subtropical Amazonian climate. The granular skeletons were optimized to use the proportions that would give the greatest density to the concrete matrix, resulting in greater mechanical resistance but maintaining the permeability. Two granulometric combinations with different packing densities were studied, as well as 3 w/c ratios and 3 contents of cement paste. The mixtures were subjected to simulations of intense and successive rainfall. The ability to reduce runoff in a densely built-up area prone to frequent flooding and inundation was evaluated, as well as the characteristics of the area and volume of the internal and superficial pores.

2. MATERIALS AND METHODS

Cava pebble, a coarse aggregate traded in the region, was used. The coarse aggregates were characterized according to their granulometric composition [35] and classified into 3 specific ranges: from 4.75 mm to 9.5 mm (passing through the 3/8" sieve, retained in the No. 4 sieve, which will be referred to as particle size 1); in diameter from 2.38 mm to 4.75 mm (passing through sieve No. 4, retained in No. 8, which will be referred to as particle size 2); and in diameter between 1.19 mm to 2.38 mm (passing through sieve no. 8, retained in sieve no. 16, which will be referred to as particle size 3). The grains were then characterized in terms of specific weight [36], unit weight [37], porosity [37] and water absorption rate [36] (Table 2). It was decided to use Portland cement CP II E 32 because its basic composition contains between 6% and 34% blast furnace slag, which gives the material a lower heat of hydration [38].

Next, a study of packing density of the granular skeleton was performed with binary combinations between particle size 1 and 2, and between particle size 1 and 3. Through preliminary studies, we defined 2 granular combinations: M1, with 77% of particle size 1 and 23% of particle size 2, and 41% voids in the granular skeleton; and M2, with 75% of particle size 1 and 25% of particle size 3, and 36% voids in the granular skeleton [39]. Finally, 18 mixtures were developed in which the cement paste content and w/c ratio were varied to evaluate the effect of cement paste content, water consumption, and granulometric arrangement on the porosity properties and performance of permeable concretes. The mixtures developed and the consumption of materials are summarized in Table 3.

The materials were mixed in an inclined shaft mixer with a capacity of 200 litters, and the order and mixing times were adopted according to Figure 1. Prismatic samples of 400 mm length and width and 100 mm height were prepared. The plates were compacted in a single layer (100 mm) with a 55 kg metal roller, as compaction with a metal roller has been successfully used in permeable pavements for use in roadways for light traffic and people [40–42]. The specimens were demolded after 48 hours and cured submerged in a water reservoir for 28 days.

2.1. Rain test

The rainfall simulation procedures of this study aimed to evaluate the occurrence of runoff over drainage layers of permeable concrete during intense, short, and successive rainfall events. The hyetogram based on the method of PILGRIM and CORDERY [43] was used as the basis for modeling the rainfall simulations, which considers that the design rainfall events do not represent the entire storms, but intense periods within the storms. For this purpose, a device was developed based on the studies of [44] and [45]. The device consists of a box measuring approximately 500 × 500 × 500 mm, isolated from the external environment by a glass chamber measuring 420 × 420 × 500 mm with an opening at the top.

Above the chamber, a set of five 25 mm PVC tubes with 0.6 mm holes, arranged in parallel and equally spaced, was placed. The set was connected to a 500-liter reservoir, with a base positioned at the same height as the longitudinal axis of the pipe. The system was equipped with two gutter systems: one to collect water that

Table 2: Characterization of coarse aggregates.

PARTICLE SIZE	SPECIFIC WEIGHT (dm/cm^3)	UNIT WEIGHT (dm/cm^3)	WATER ABSORPTION (%)	POROSITY (%)
1	2630,42	1566,89	1	40,43
2		1501,24		42,93
3		1492,57		43,26

Table 3: Material consumption for each mixture (Mn. AB, where n is the granulometric combination used (M1 or M2), A is the cement paste content (0.27, 0.29 or 0.31) and B is the ratio w/c (0.30, 0.32 or 0.34).

MIX	AGGREGATES			PASTE CONTENT	w/c RATIO	CEMENT CONSUMPTION (kg/m³)	WATER CONSUMPTION (l/m³)
	PARTICLE SIZE 1 (kg/m³)	PARTICLE SIZE 2 (kg/m³)	PARTICLE SIZE 3 (kg/m³)				
M1.27.30	1208,67	361,03	–	0,27	0,30	430,0	130,32
M1.29.30	1208,67	361,03	–	0,29	0,30	461,9	139,97
M1.31.30	1208,67	361,03	–	0,31	0,30	493,7	149,62
M1.27.32	1208,67	361,03	–	0,27	0,32	416,8	134,71
M1.29.32	1208,67	361,03	–	0,29	0,32	447,6	144,69
M1.31.32	1208,67	361,03	–	0,31	0,32	478,5	154,67
M1.27.34	1208,67	361,03	–	0,27	0,34	404,3	138,85
M1.29.34	1208,67	361,03	–	0,29	0,34	434,2	149,13
M1.31.34	1208,67	361,03	–	0,31	0,34	464,2	159,42
M2.27.30	1266,45	–	422,15	0,27	0,30	430,0	130,32
M2.29.30	1266,45	–	422,15	0,29	0,30	461,9	139,97
M2.31.30	1266,45	–	422,15	0,31	0,30	493,7	149,62
M2.27.32	1266,45	–	422,15	0,27	0,32	416,8	134,71
M2.29.32	1266,45	–	422,15	0,29	0,32	447,6	144,69
M2.31.32	1266,45	–	422,15	0,31	0,32	478,5	154,67
M2.27.34	1266,45	–	422,15	0,27	0,34	404,3	138,85
M2.29.34	1266,45	–	422,15	0,29	0,34	434,2	149,13
M2.31.34	1266,45	–	422,15	0,31	0,34	464,2	159,42

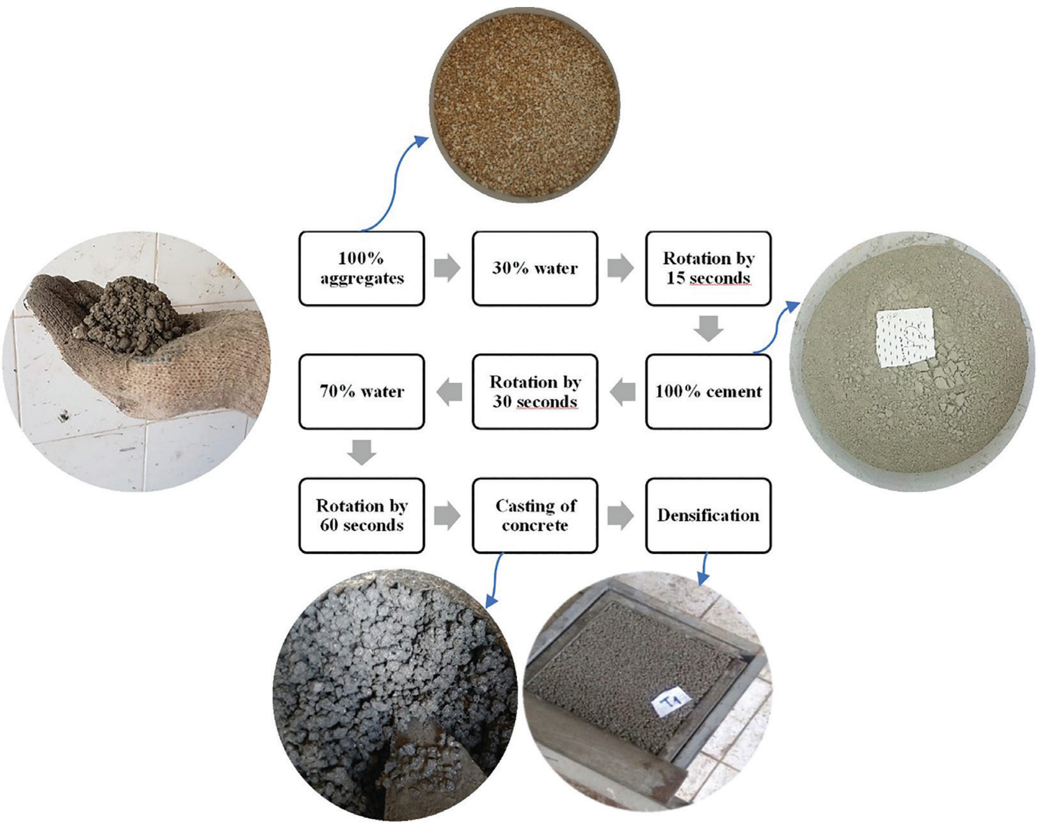

Figure 1: Material release, mixing time and compaction process.

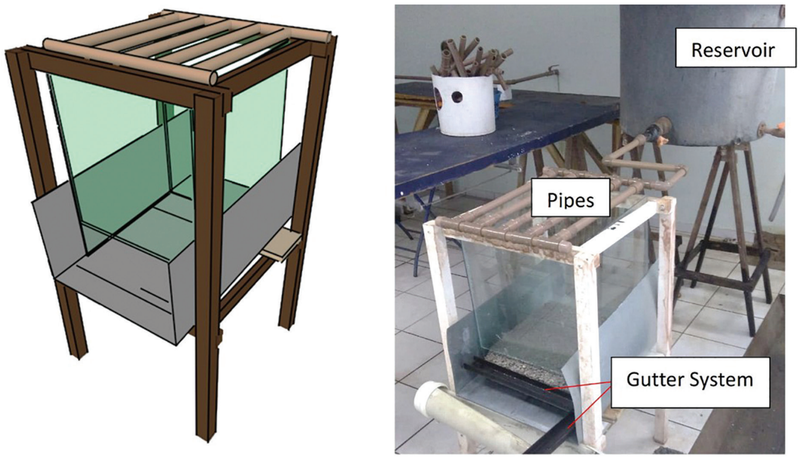

Figure 2: Rain device model (left) and device in use (right).

would run off superficially through the plate, and another to collect water that would percolate through the concrete matrix. The set is detailed in Figure 2.

Preliminary studies were conducted to investigate the relationship between slope, flow rate, and the occurrence of runoff in permeable concrete specimens. It was found that a flow rate of 157 mm/h and a slope of 6% caused the occurrence of surface runoff – no runoff was observed at lower flow rates and slope combinations. Therefore, the flow rate on the device was standardized to 157 mm/h and the slope to 6% [46].

The samples were subjected to four rainstorms simulations of 15 min duration each, with intervals of approximately 3 to 4 minutes between each test, during which time the plates could be removed from the device, weighed, and reinserted for the next rain simulation. Each 15-minute test corresponds to the approximate amount of precipitation that falls during each rainfall event in the municipality of Belém (about 40 mm), which is characterized by rapid and intense rainfall [47]. The repetition of the simulations aimed to evaluate the variations in performance in the samples with increasingly saturated porous matrix.

At each stage of the test, the volume of water that had precipitated through the concrete slabs and that was running off the surface was weighed in relation to the total volume of water that had precipitated. From the ratio between the volume that drained and the total volume, the coefficients for surface runoff were determined for each of the samples tested. Tests of dry concrete specific weight [48], permeability coefficient [49], and flexural strength [50] were then performed to determine the properties of the material in the cured state.

2.2. Porosity

The concrete slabs were cut into cubic samples to perform tests to determine the percentage of isolated, effective, and total pores using the equations presented by [51]. Finally, the digital image processing procedure (DIP) was performed using the ImageJ program to evaluate the superficial and internal pores obtained in cross-sections of two random cubic specimens with dimensions 100 × 100 × 100 mm. The test was performed on 3 different samples of each mixture, resulting in 54 images for internal pores and 54 for superficial pores.

The DIP method has the advantage of allowing a characterization of the concrete matrix with simple means, in chronological order: photographic acquisition of the cross-section and surface of the sample; conversion of the image type to 8 bits; adjustment and standardization of brightness and contrast; adjustment and standardization of the percentage of noise in the image; characterization of the number and dimensions of the outliers identified in the image. The procedure is illustrated in Figure 3.

Then, the linear correlation between the variables of interest in this study was applied using the Pearson coefficient (r) to confirm or exclude proportional relationships between the results obtained. Pearson coefficient (r) is an indicator of correlation between variables, i.e., correlation coefficients of 0.70 or higher represent a high degree of association between scores, coefficients between 0.40 and 0.69 represent moderate correlation, and coefficients below 0.40 represent low correlation between variables. The correlations were also assessed as positive (when one parameter increases, the other also increases) or negative (when one parameter increases, the other decreases) [52].

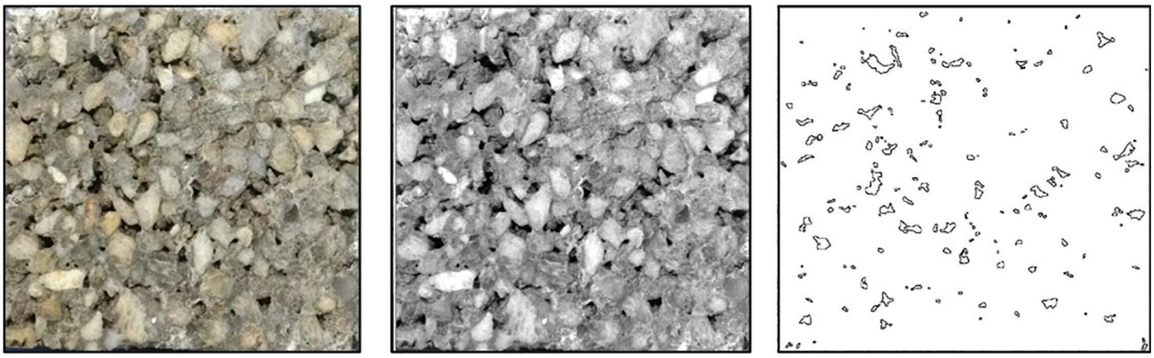

Figure 3: Example of image treatment: (A) Photographic record; (B) Setting for 8-bit; (C) Pore characterization. counting and sizing.

2.3. Estimate of runoff

Finally, an estimate of the reduction in runoff due to the replacement of impervious concrete and asphalt pavements with permeable concrete pavements was made. The region corresponding to the area of influence of the 3 de Maio drainage channel in the municipality of Belém, in the Brazilian state of Pará, was selected for analysis because it is a densely built-up floodplain where surface sealing is already advanced (Figure 4).

In studies of [28] and [29], an 200% increase in the frequency of flooding can be observed in the region corresponding to the area of influence of the 3 de Maio drainage channel, between 2012 and 2017, as a result of the decreasing functionality of the local drainage system.

According to [53], considering urban growth and demographic densification in recent decades, the percentage of acceptable permeability would be between 20 and 25% of the total area of a densely urbanized region. However, the evaluation of the areas with the QGis program showed that only 13% of the surfaces in this region are suitable for surface water infiltration. About 88% of the region is covered with concrete (75%) or asphalt (13%), so proposals to increase permeable surfaces are desirable.

The region is moderately populated with an average of 119 inhabitants/hectare. Macro-drainage works were carried out between 1980 and 2000, but they do not prevent flooding after rain events [54]. According [54], the region's low permeability, population density, and built-up area, combined with its low slope, result in unfavorable surface drainage conditions.

The rational method equation (Equation 1) was used for flow rate calculation [55]. The information obtained from the land use and settlement map was used to calculate the runoff coefficient, from which the final runoff was calculated from the weighted averages of the coefficients on different surfaces.

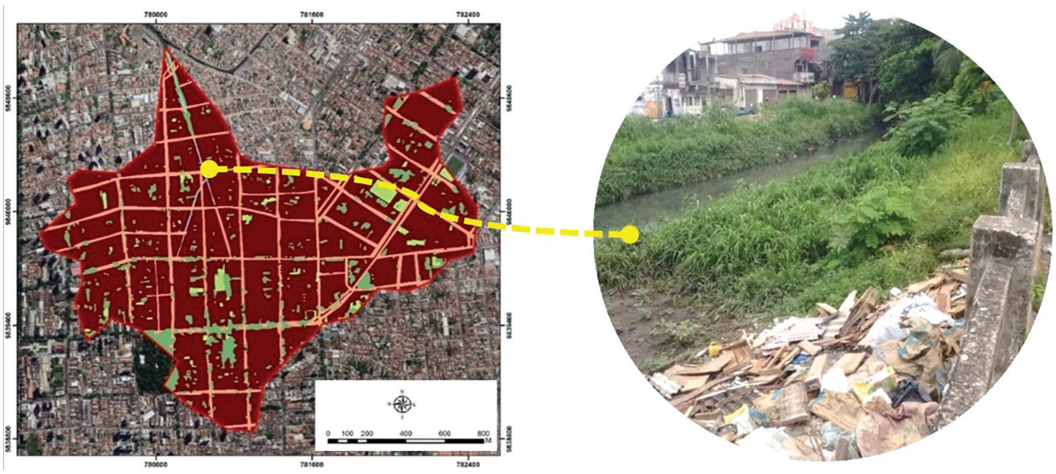

Figure 4: Area of influence of the 3 de Maio drainage channel, Belém. In green: vegetation and grass; in blue: water; in red: impermeable concrete surfaces; in pink: asphalt. Highlighted is the deterioration of the drainage channel, in an area where garbage is dumped and the structure is damaged.

$$Q = \frac{C \cdot I \cdot A}{360}, \quad (1)$$

where Q is the flow rate (m^3/s); C is the runoff coefficient obtained from the weighted averages of the coefficients assumed for each surface, which varies from 0 to 1; I is the rainfall intensity (mm/h); and A is the analysis area (ha). The rainfall equation proposed by [56], detailed in Equation 2, was used to calculate rainfall intensity.

$$I = \frac{(k \cdot TR^a)}{(t+b)^c}, \quad (2)$$

where I is the rainfall intensity, in mm/h; TR is the return period, in years; t is the duration of rainfall, in minutes; K, a, b and c are constants of the intense rainfall equation that are adjusted depending on the location for which the equation is used. For the studied region, rainfalls of 15 minutes duration and a return period of 25 years were considered. K, a, b and c were defined as 960.58, 0.0954, 9.7993 and 0.7245, respectively [56]. The calculated intensity was 127.53 mm/h.

Finally, different percentages of replacement of impervious layers with permeable concrete layers were simulated to comparatively evaluate the potential flow reduction from the insertion of materials with surface runoff coefficients lower than those in operation. Replacements of 10, 20, 30, 40 and 50% were considered, firstly on sidewalks, then the same percentage of replacement on paved roads for vehicular traffic, to evaluate the potential reduction in surface runoff from the introduction of permeable concrete technology. The estimates were aimed at assessing the potential for reducing surface runoff by using permeable pavements, and replacement percentages were set empirically until the minimum index of permeable surfaces in the region-20%-was reached.

The estimation was limited to the initial analysis of the pavement performance. It considered 20 cm of coarse aggregate with a void index greater than 30% for the lower base course, as well as the use of a waterproofing layer to prevent surface water from draining directly into the soil, thus preventing solid particles from rising from the base course.

Asphalt lanes were standardized with an average width of 12 meters, surrounded on both sides by pedestrian walkways. Each pedestrian walkway was considered as a conventional concrete pavement with a width of 1.2 meters. In this scenario, for every m of length (12 m^2) of paved road, there is about 2.4 m^2 of sidewalk, which resulted in approximately 55,000 m^2 of sidewalk – about 3.4% of all concrete coverage in the region. In addition, the estimates were limited to light vehicle and pedestrian circulation lanes, without considering, for example, possible parking lots and uncovered garages present in the region.

3. RESULTS

3.1. Properties of the mixtures

The results of specific weight in the two mixtures are summarized in Figure 5. For M1, the specific weight ranged from 1.67 to 1.81 kg/dm^3, and for M2, from 1.75 to 1.94 kg/dm^3. These values are consistent with specific weight values normally observed for permeable concretes, which typically range from 1.60 kg/dm^3 to 2.0 kg/dm^3 and are lighter than conventional concretes due to the high porosity of the concrete matrix [10]. M2 mixtures, with lower void content in the granular skeleton, exhibited higher packing density. The results agree with the findings of other studies where it was found that the reduction in particle size leads to less porous and denser mixtures [57, 58].

Varying the w/c ratio resulted in the densification of M2; M1, in turn, did not show the same performance. The limitations in M1 densification are related to two parameters: the fluidification of the cement paste and the increase in the cement paste content were not sufficient to fill the voids of the concrete matrix; and the compaction method used was not sufficient to increase the packing of the grains (Figure 6).

The values of total porosity found in most mixtures are within ranges normally reported in the international literature, from 15 to 35% [10] (Figure 7). In M1, the total porosity ranged from 26% to 39%, and in M2 from 21% to 33%. The effective porosity of the mixtures ranged from 17% to 32% in M1 – with M1.27.34 being an outlier with 39% total porosity and 31% effective porosity. M2 showed an effective porosity between 13% and 24%. Mixtures M1 and M2 showed between 7% and 10% isolated pores.

As all samples were subjected to the same mixing, compaction and curing process, the discrepant results in M1.27.34 are related to the dosage of cement paste and water: at the low cement paste content, despite the

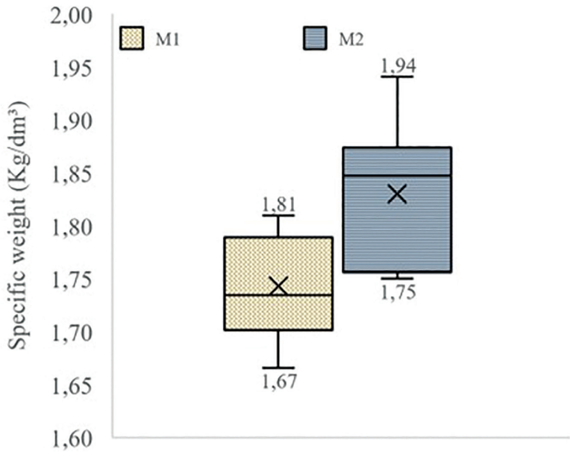

Figure 5: Specific weight of groups M1 and M2.

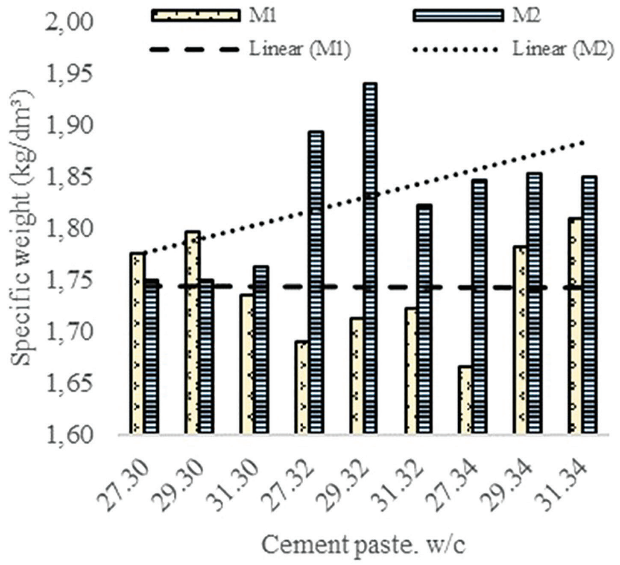

Figure 6: Specific weight for variations in cement paste content and water/cement ratio. The addition of water, in general, allowed the densification of samples from the M2 group.

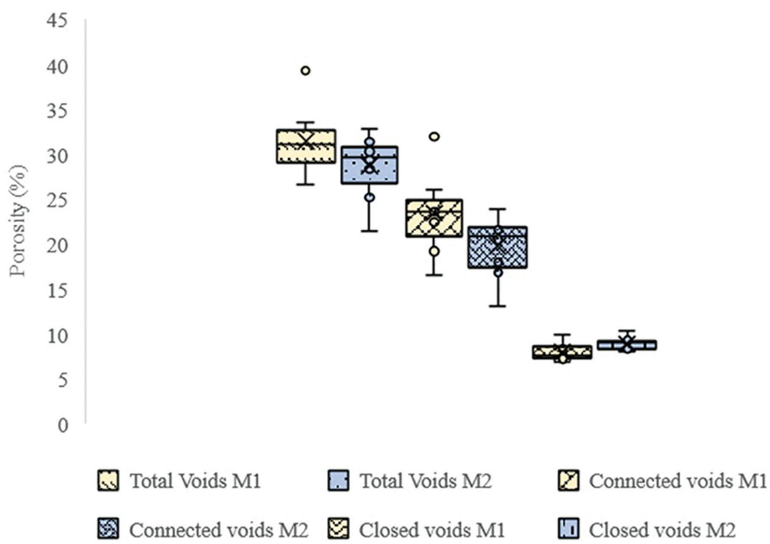

Figure 7: Porosity of granulometric groups M1 and M2.

high amount of water, there was insufficient fluidification to achieve adequate compaction of the granular skeleton with the applied load, resulting in higher porosities.

For M1, the permeability coefficient ranged from 1.14 $\times 10^{-2}$ m/s to 6.85 $\times 10^{-3}$ m/s, while for M2 it ranged from 8.26 $\times 10^{-3}$ m/s to 2.37 $\times 10^{-3}$ m/s (Figure 8). The values obtained are superior to permeability coefficients normally observed in similar studies, which range between 2.0 $\times 10^{-3}$ and 5.4 $\times 10^{-3}$ m/s [10, 59], and to the regulations for permeable concrete pavements, which recommend permeability coefficients from 1.0 $\times 10^{-3}$ to 1.4 $\times 10^{-3}$ m/s [12, 38]. As expected, M1 exhibited greater potential for water infiltration, due to the higher presence of interconnected pores in the concrete matrix. For M2, it was observed that the increase in the w/c ratio and consequently the fluidification of the cement paste strongly reduced the permeability potential of the mixtures (Figure 9).

It was found that the reduction of the characteristic diameter of the aggregates in M2 reduced the linear relationship between the permeability coefficient and the effective porosity (Figure 10). This behavior was

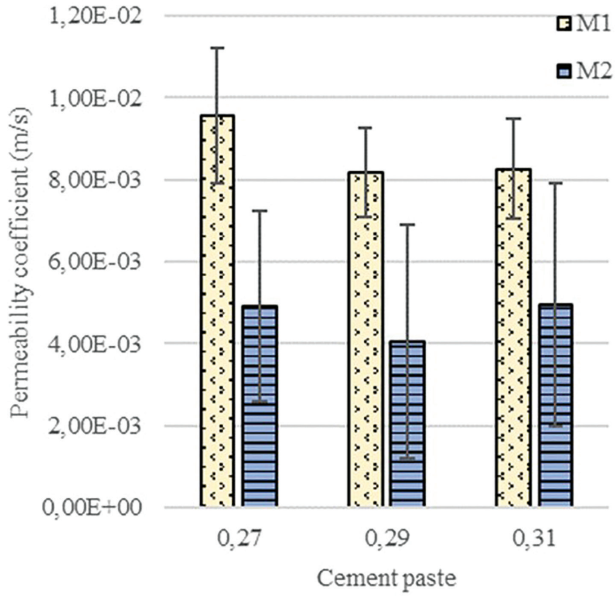

Figure 8: Permeability coefficient for 0,27, 0,29 and 0,31 cement paste contents.

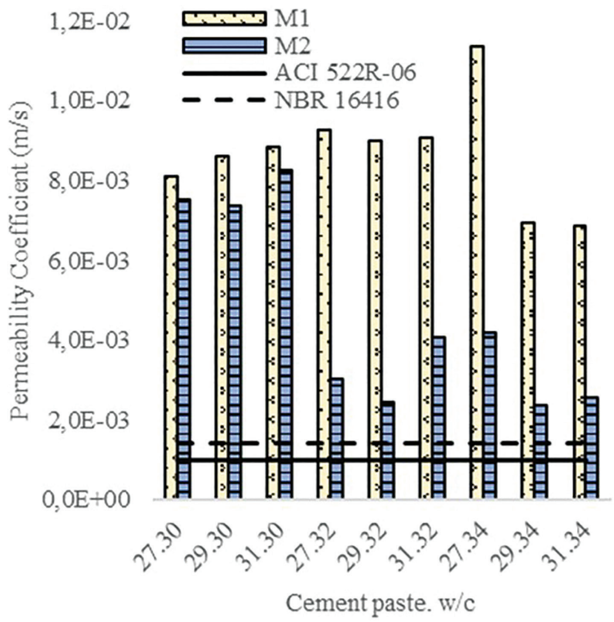

Figure 9: Permeability coefficient for with variations in cement paste content and water/cement ratio. In particular, the M1 specimens showed a permeability coefficient well above the minimum recommended by the regulations.

related to the formation of impermeable niches in the M2 mixtures, whose diameter was up to four times larger than that of the coarse aggregates used. These niches were generated by the increase and fluidification of the cement paste, linked to the limitations in the mixing and release process of the materials (Figure 11). The niches generate points of low permeability within the concrete matrices, and cause samples with a similar percentage of pores to eventually have discrepant permeability coefficients [60].

The mixtures showed flexural strength ranging from 1.43 MPa to 2.82 MPa in M1, and from 1.69 MPa to 2.81 MPa in M2. The flexural strength varies between 1 and 3 MPa in similar studies, but it can reach higher values through the incorporation of additives [61]. As expected, M1 also presented a flexural strength reasonably lower than M2, due to the greater porosity of the mixtures (Figure 12). The use of larger grains reduced the packing density of the M1 granular skeleton, resulting in less cohesive mixtures and greater potential for fracture rupture between the cement paste and the aggregates.

All mixtures showed satisfactory performance for use on pedestrian walkways, and M1 with a w/c ratio of 0.30 and M2 with w/c ratio equal to or greater than 0.32 showed satisfactory flexural strength results for use in pavements on light vehicle traffic. It was also verified that the increase in the w/c ratio to 0.32 resulted in a decrease in the flexural strength at M1. In turn, at M2, the increase in the w/c ratio allowed the fluidification of the cement paste and the greater packing of the mixtures resulted in higher strengths (Figure 13). It was observed, however, that the reduction in the characteristic diameter of the coarse aggregates and the greater packing density of the mixtures did not enable a significant increase in mechanical strength in M2 compared to M1 mixtures. The mechanical performance observed in mixtures with smaller aggregates is associated with the low presence of spaces between the pores, which facilitates the evolution of cracks and culminates in concrete fracture [11].

Through Digital Image Processing of prismatic samples, it was found that the matrices in M1 had a smaller number of inner pores, which ranged from 1.1 to 1.9 mm^2, and in M2 from 0.8 to up to 1.7 mm^2.

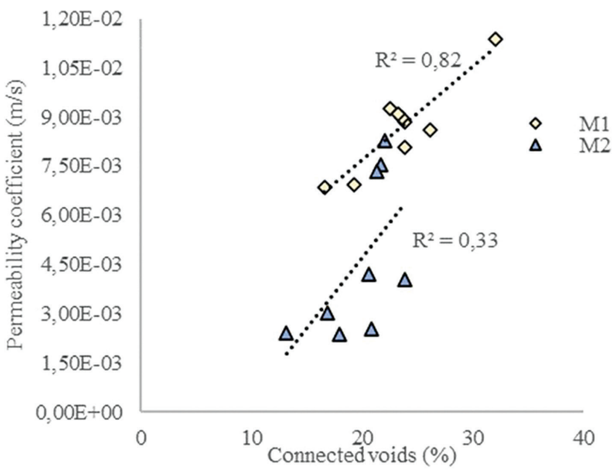

Figure 10: Relationship between permeability coefficient and connected pores. As impermeable niches are formed in the concrete matrix, the relationship between connected pores and permeability is reduced.

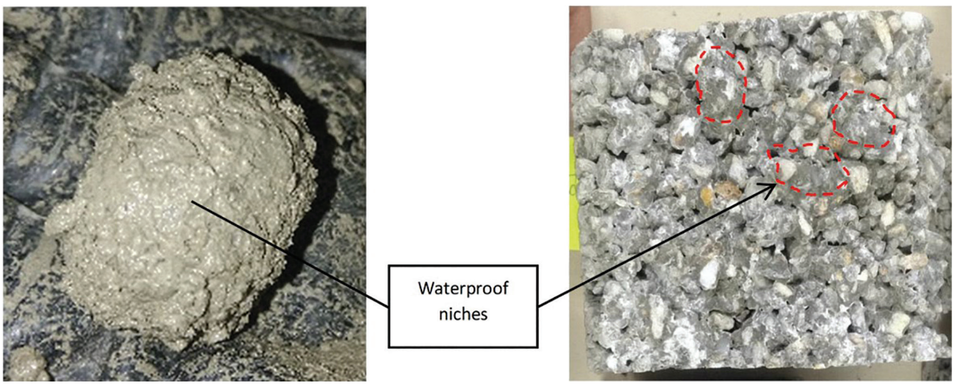

Figure 11: Presence of waterproof niches in the mixtures, up to 20 mm in diameter.

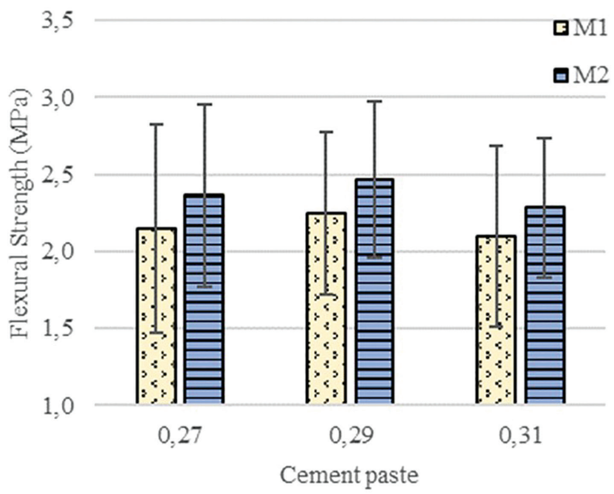

Figure 12: Flexural strength for different cement paste contents.

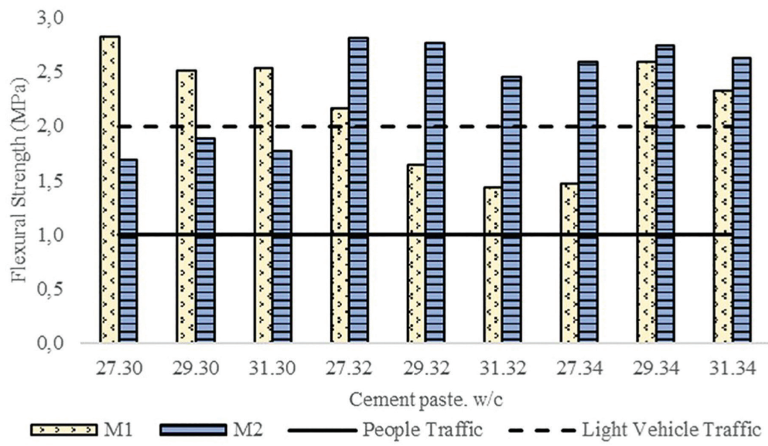

Figure 13: Flexural strength for variations in cement paste content and water/cement ratio. Addition of water to M2 mixtures increased the strength of concrete matrices.

Regarding the image analysis of the superficial pores, the same patterns were observed (M1 with less and larger pores), however the differences were more pronounced. M1 had an average of 150 superficial pores ranging in size from 5.5 to 10.2 mm^2 while M2 had up to 300 pores ranging from 1.4 to 3.3 mm^2 (Figure 14). The differences in pore size were related to the characteristic diameter of the coarse aggregates used in each mixture, which influenced the compactness of the mixtures.

Furthermore, it was observed that the surface pore area corresponded to approximately 10% of the total area of the M1 samples, and around 7.5% of the total area of the M2 samples. It was also found that the compaction of the mixtures through the addition of cement paste was not determinant for significant variations in the total area of superficial pores (Figure 15).

3.2. Rainfall simulations

Finally, four rain events with a flow rate of 157 mm/h and a duration of 15 minutes were simulated for each sample. More porous and permeable samples showed greater capacity for absorbing and retaining surface water, represented by the ratio Mi/Mf in mass, initially (Mi) and after (Mf) the rainfall simulation (Figure 16). However, it was observed that in all samples there was loss of absorption and retention capacity as the tests progressed with simulated rain, in agreement with what was observed in similar studies [24].

It was also observed that with each rain event, not only did the absorption and storage capacity of the surface water decrease, also the risk of runoff increased. In M1, the samples showed runoff from 0 to 0.0035 (i.e., 0.35% of the total water volume would flow off superficially) when the 4th rain simulation was conducted (Figure 17). In M2, samples with lower porosity and reduced surface water retention and absorption capacity,

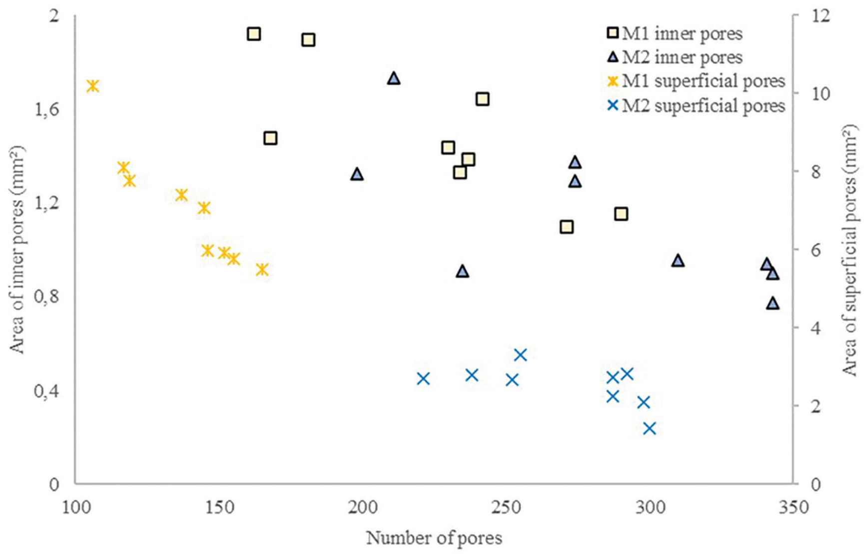

Figure 14: Area of inner and superficial pores, and number of pores in mixtures M1 and M2.

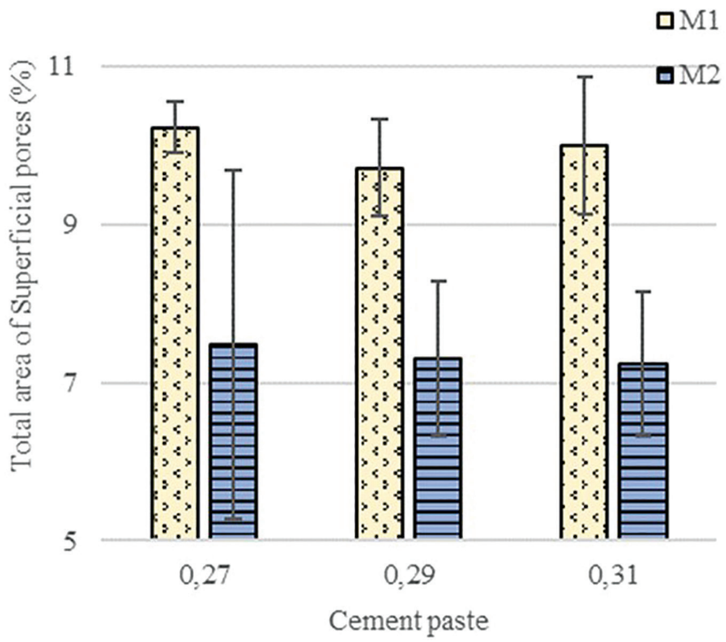

Figure 15: Total surface pore area for each cement paste content.

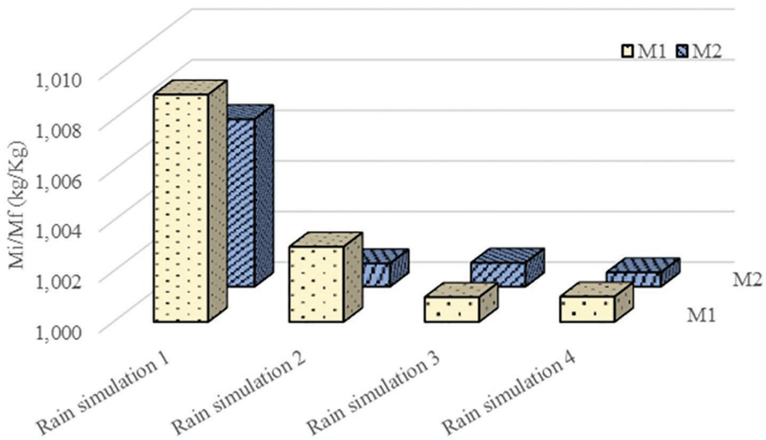

Figure 16: Loss of water storage capacity at each event of heavy rain in M1 and M2.

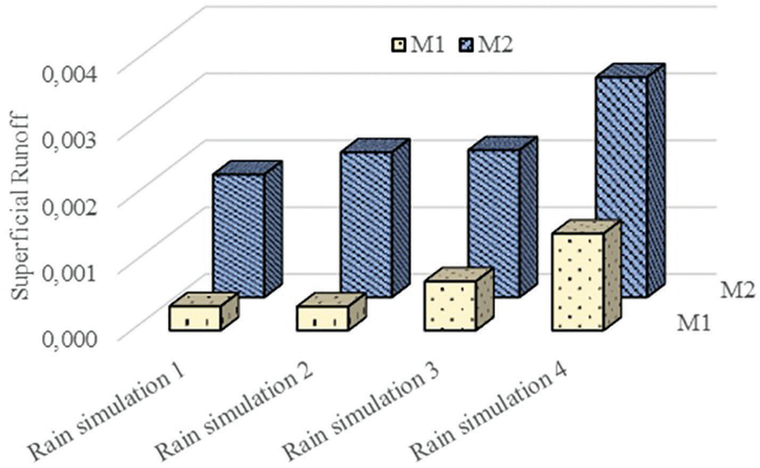

Figure 17: Occurrence of runoff after each rain simulation in M1 and M2.

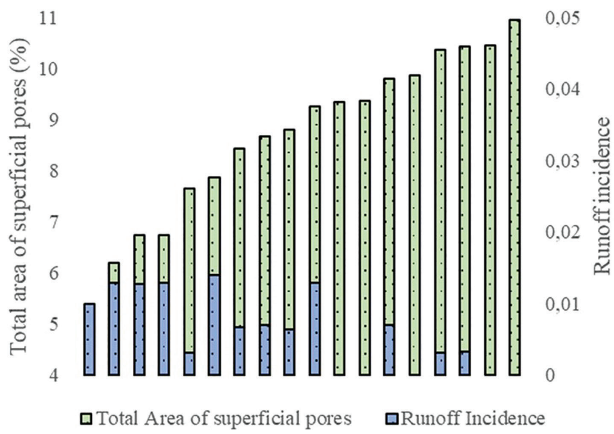

Figure 18: Reduction of surface pore area and incidence of runoff.

there was a runoff risk of up to 0.0035 from the first simulated rainfall event. The total average runoff after four rain simulations was 0.0029 (0.3%) for M1, and 0.0090 (0.9%) for M2.

At the last simulation, the samples showed maximum runoff coefficient. Previous studies have pointed out the risk of surface runoff due to the loss of rainwater absorption capacity in permeable concrete layers, which is mostly related to the presence of solid particles in the rainwater that fill the pores of the structure and prevent the passage of water [62, 63]. In the simulations performed in this study, it was found that the loss of absorption capacity of the pavement can also be associated with the saturation of the concrete layer by water, since no solid particles were trapped.

It is observed in Figure 18 that the reduction in superficial pores is related to a greater risk of runoff occurrence. The M2 samples, with a relative reduction in superficial pores, showed a high increase in superficial runoff. In turn, the variations in the cement paste content strongly influenced the occurrence of runoff: in both groups, the increase in cement paste increased the occurrence of runoff (Figure 19). Finally, it is noteworthy that when the concrete layers were saturated and runoff occurred, no mixture presented total runoff greater than 0.016 even after four rain simulations, which would guarantee exceptional performance of permeable concrete in situations of rainfall typical of the region where this study was conducted.

Finally, Pearson's linear correlation coefficient was calculated to evaluate the degree of correlation between the parameters analyzed in this study, where p is the p-value of statistical significance less than or equal to 0.05 and r is Pearson's linear correlation coefficient (Table 4). The runoff is moderately correlated to several variables, highlighting the moderate negative relationship with the effective porosity ($r = -0.58$) and the total porosity ($r = -0.57$). The relationship between runoff and porosity (effective and total) of the concrete matrix is justified by the capacity of the permeable layer to drain surface water quickly, which is related to the presence of interconnected pores in the matrix. The moderate correlation with the specific weight and permeability of the

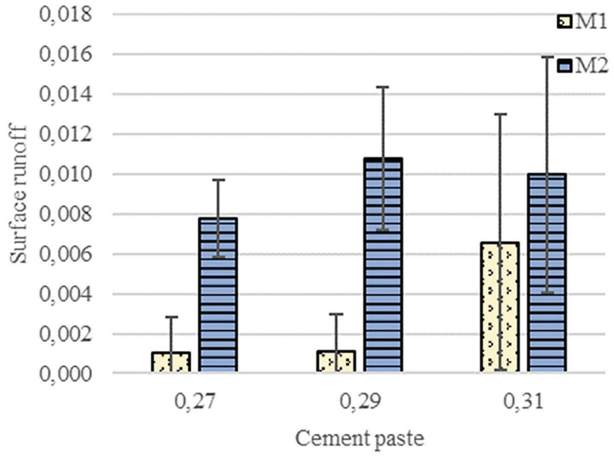

Figure 19: Runoff coefficient for each cement paste content.

Table 4: Linear correlation of the runoff coefficient with the variables considered in this study.

RELATION 1	RELATION 2	r	P-VALUE	CORRELATION	TYPE	VARIANCE
Surface runoff	**Specific weight**	0,51	p < 0,05	Moderate	Positive	0,26
	Effective porosity	−0,58	p < 0,05	Moderate	Negative	0,34
	Total porosity	−0,57	p < 0,05	Moderate	Negative	0,32
	Permeability	−0,50	p < 0,05	Moderate	Negative	0,25
	Total area of superficial pore	−0,70	p < 0,05	Strong	Negative	0,49
	Average superficial pore size	−0,65	p < 0,05	Moderate	Negative	0,43

specimens could also be related to the porosity of the concrete matrix, since more porous specimens had higher permeability levels and lower specific weight.

It was identified that the occurrence of runoff in the permeable concrete specimens in this study can be strongly correlated with the total area of superficial pores (r = −0.70), and moderately correlated with surface pore size as well (r = –0.65), i.e., the larger the surface area and pore size, the less likely the occurrence of surface runoff. In another study, a strong correlation was found between the surface pores and the sound absorption of concrete samples, especially at low frequencies, which improves the environmental performance of the material for the retention and dispersion of surface water, but also for the attenuation of urban noise [64].

3.3. Simulation of runoff reduction

For estimation purposes, the potential use of permeable pavements in a densely populated micro basin with low permeability in the municipality of Belém, Pará, was evaluated. CHOW *et al.* [65] determined runoff coefficients for various pavements for a 25-year return period: Concrete pavements 0.88, asphalt pavements 0.86, and grass pavements 0.46. This estimate assumed that the permeable concrete pavements had a flexural strength of at least 2 MPa, i.e., suitable for light vehicular traffic, and considered the highest runoff coefficient determined in the rainfall simulations of 0.016 (1.6% of the total flow volume).

The replacement of 50% of conventional concrete sidewalks by permeable concrete layers presented a potential reduction of approximately 8% of the total surface water flow rate (from 84000 to 77000 l/s), and an increase in drainage covers from 13% to 20% – enough to reach the minimum level of permeability for densely urbanized regions (Figure 20). Otherwise, if only 10% of paved roads are replaced by layers of permeable concrete, the percentage of permeable layers would increase by practically twice, reaching the level of 20% (Figure 21).

Finally, the permeable pavements considered in this study presented a reduction in the surface runoff in up to 94% compared to conventional concrete pavements and asphalt, and up to 89% in relation to grassy surfaces.

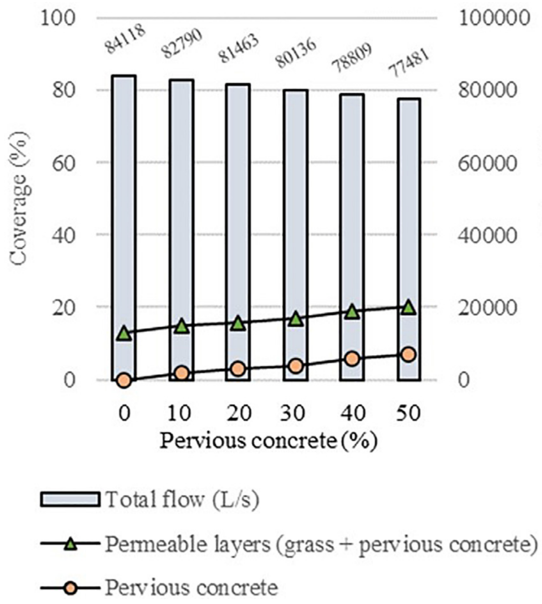

Figure 20: Replacement of conventional concrete sidewalks by permeable concrete.

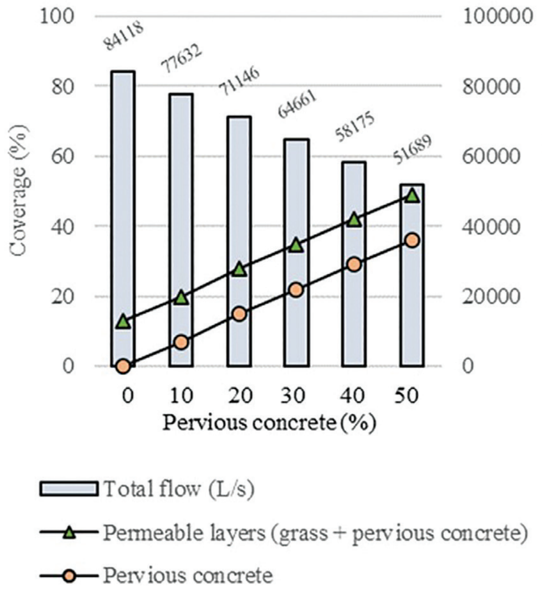

Figure 21: Replacement of conventional asphalt pavements for light vehicle traffic by permeable concrete.

4. CONCLUSIONS

The present work was developed with the aim of evaluating the technical feasibility of permeable concrete pavements that can meet the mechanical and hydrological requirements of regions with heavy rainfall. For this purpose, granulometry, w/c ratio and cement paste content were considered as control variables, resulting in 18 mixtures. The results stand out:

- All samples in the second particle size group (M2) presented a higher risk of runoff occurrence during heavy rainfall simulation due to their higher packing density. This finding can be related to the dimensions of the superficial pores, which made it more difficult for liquids to infiltrate, and the low discharge speed of stored water;
- Surface runoff can be correlated with several variables, highlighting the moderate negative relationship with the effective porosity (r = − 0.58), due to the relationship of this variable with the potential to absorb and drain surface water quickly;
- It was observed that the occurrence of runoff can be related to the total area of superficial pores (r = − 0.70) − the larger the total area of superficial pores, the lower the incidence of runoff.

It is noteworthy that the samples were subjected to simulations with rainfall volume greater than the rainfall intensity calculated for the region, and in all experiments the runoff coefficient was less than 0.05. Such performance is considered extremely satisfactory for the initial validation of draining pavements.

Finally, were carried out performance estimates of permeable concrete surfaces in a densely urbanized region with low permeability, considering intense rainfall and a 25-year return period. The results suggest that the technology has great potential as a sustainable alternative to conventional surface drainage in the region, with a significant reduction in runoff as well as an increase in areas with drainage potential. Supplemental studies are needed to provide parameters for the cost of replacing existing pavements with permeable concrete pavements, pavement clogging, and maintainability.

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